U. S. Department of the Interior
Bureau of Land Management

Alaska State Office
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Anchorage, Alaska 99513

BLM-Alaska Technical Report 15
BLM-AK-PT-92-021-3045-985
March 1992

Log Analysis of Aurora 890-#1, OCS-Y-0943 Well, Offshore of the Arctic National Wildlife Refuge 1002 Area, Northeast Alaska

Arthur C. Banet, Jr.

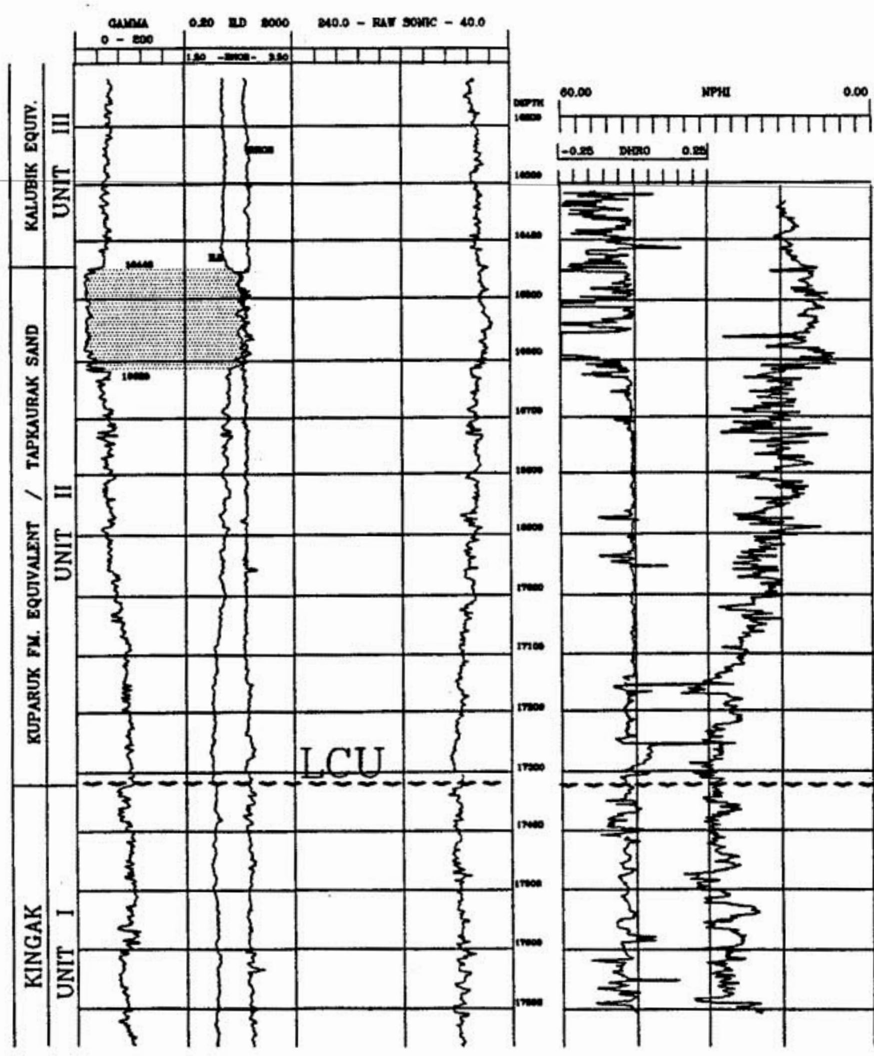

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Table of Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

ABBREVIATIONS

A number of abbreviations are used in this text. Many have a "non-standard appearance" because periods are eliminated to simplify punctuation and to maintain a balanced appearance for the reader. This strategy becomes very evident in the discussion of the log units and their characteristics where the inclusion of standard punctuation could make the text confusing. Probably the most noticeable non-standard appearance is where well depths or ranges of depth pertinent to the logs are not shown (e.g. as "930 to 9518" rather than "930 ft. to 9518 ft.") because the many repetitions become redundant and arduous to follow. Thus, all log-related measurements are from KB (Kelly Bushing or rotary table) without abbreviations. Specific measurements of distance, e.g. from contacts or depths of other wells, retain feet or the abbreviation "ft." Other abbreviations are listed below.

Geochemical data

%Ro	vitrinie reflectance in oil
G.P.	Genetic Potential (S1 + S2)
OI	Oxygen Index (S3/TOC)
P.I.	Production Index (S2/TOC)
S1, S2, or S3	peak designations from pyrolysis
TAI	Thermal Alteration Index
TOC	Total Organic Carbon

Well log descriptions

API	American Petroleum Institute for oil gravity and gamma ray counts
BHC	bore hole compensated sonic log
DT	delta t - change in interval transit time
DTs	delta t shear- change in shear wave transit time
GR	natural gamma ray log
ILD	deep focus induction log
ILM	medium focus induction log
N, E, W, S	north, south , east, west
SFL	shallow focus Dual Induction Resistivity log
SP	spontaneous potential (log +/- mv)

Other

cc	cubic centimeter
ft	foot or feet
g	grams
gal	gallons
lbs	pounds
µ	micro

Acknowledgements

Despite the politically sensitive nature of oil and gas studies in and around the Arctic National Wildlife Refuge 1002 area, the Division of Minerals (AK-980) and Branch of Mineral Assesment (AK-985) have supported the efforts to continue the ongoing analysis of pertinent geologic data. Without this support, especially from the staff of AK-985, I would be without the opportunity to contribute to the ANWR assessment and my geologic profession. I also had the good fortune to use the sample viewing facilities at the Geologic Materials Center which was an important contribution to this work. My appreciation is both professional and personal.

In addition I wish to acknowledge the efforts of those who have technically reviewed this manuscript. Barbara Bascle (MMS), Robert Bascle (BLM AK-985), S. M. Banet (MMS) and Tom Mowatt (BLM AK-984) have offered important observations, critiques and suggestions to some rather controversial material. In addition, Robert Bascle has provided an extensive edit of this material and shown me some rather important ways not to abuse the English language. I sincerely hope that this material reflects their professional inputs.

Log Analysis of Aurora 890-#1, OCS-Y-0943 Well, Offshore of the Arctic National Wildlife Refuge 1002 Area, Northeast Alaska

Abstract

The Aurora well, drilled in federal waters immediately offshore of the Arctic National Wildlife Refuge, 1002 area, is currently the deepest well in the Beaufort Sea (U.S.). It represents some of the most recent publicly available geological data for this remote, but important area to U.S. and Canadian exploration. Geophysical logs record 18,325 feet (5587m) of clastic section at this location. Log analyses determines that both Breakup and Brookian depositional sequences are represented. Informal names are assigned to several sandstones to facilitate comparisons to regional units.

Breakup sequence shales and locally deposited sands are from 18,325 to 15,937 feet (5585 to 4858m). The basal Unit I, is approximately 1000 feet (305 m) of Kingak Shale and is terminated by a lower Cretaceous-age unconformity (LCU). It is unconformably overlain by Unit II: a coarsening and thickening upwards sequence of shales and sandstones, culminating with the informally- named Tapkaurak sand. Unit III is mostly marine mudstone and is terminated by a lower Tertiary-age unconformity (LTU) at 15,937 feet (4858m). Notable similarities and differences exist between these sediments and coeval onshore lithologies and there are important implications pertinent to the analysis of the ANWR 1002 area.

This analysis identifies 10 units of middle Brookian and one upper Brookian sequence sediments. Individually, these units range in thickness from 473 to 3533 feet (144 to 1077 m) and are composed of mostly thin, and interbedded shale siltstone, mudstone and clay. Sediment transport directions are north to north-northwest. The major Brookian sequence sand, informally named the Oruktalik sand, had a show of gas and some minor staining, and is comparable to the Flaxman sands.

1. Introduction

Tenneco Aurora 890 #1 well OCS Y-0943 is the most recently available geological data pertinent to the Arctic National Wildlife Refuge (ANWR). The well is located approximately four miles north of Griffin Point (T.8N., R.37E.,sec.9) and approximately five miles north, 45 degrees east, of Tapkaurak Point (T.8N., R.36E., sec.1), which is the site of the Chevron KIC #1 Jago well *(figures 1 and 2)*. Although the Chevron KIC #1 Jago well is within the geographical limits of the ANWR 1002 area, it is on private corporate holdings and the data are not available for analyses.

The Aurora well was drilled from a semisubmersible platform in approximately 68 feet of water. The Kelly Bushing, from which all the log measurements

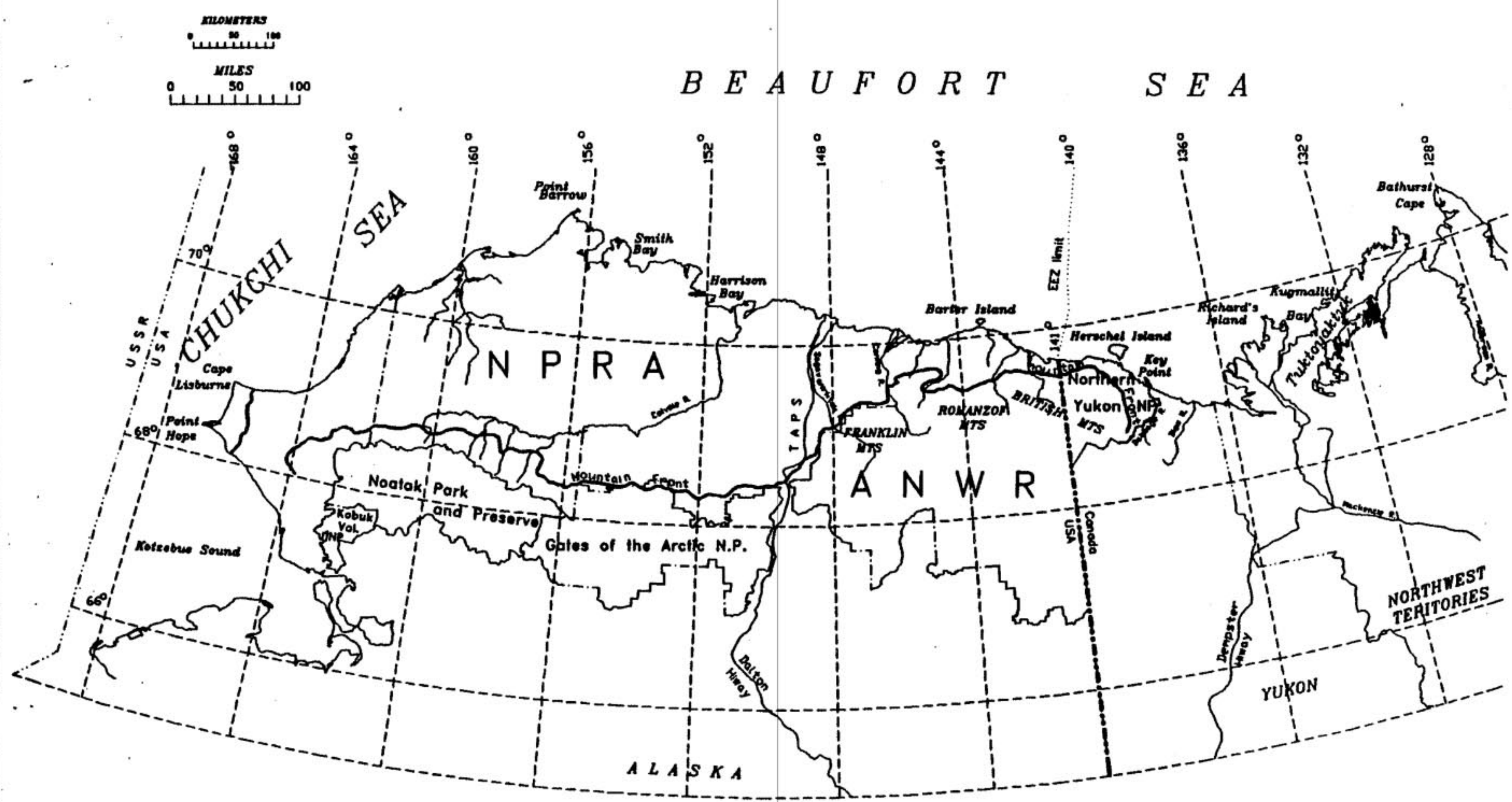

Figure 1
Index map of the Arctic showing major geographic features in Alaska, Yukon Territory and Northwest Territories

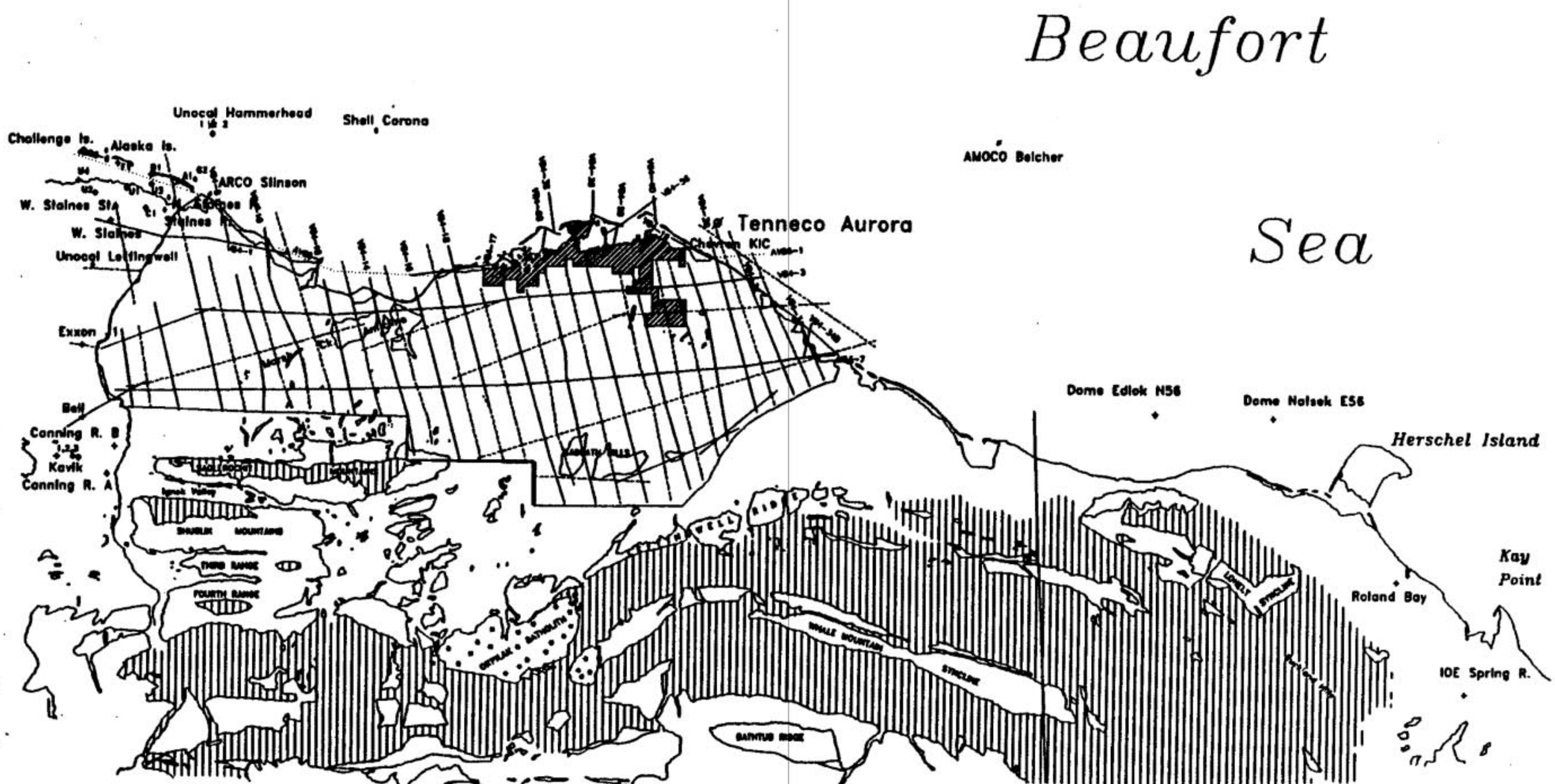

Figure 2
Aurora well location and major geographic features, including ANWR 1002 area, seismic lines, and nearest exploration wells

(pre-Ellesmerian rocks are hatched)

in this report are made, is shown as 106 feet above seafloor. It took almost a year to complete because of drilling problems. These problems include overpressure zones, stuck pipe, and well-bore sloughing which resulted in use of additives in the drilling muds (with consequent cuttings contamination). The hole was sidetracked at about 15,503 and at 16,556. Despite these problems, a total depth (TD) of 18,325 ft was reached before operations were terminated. This is the deepest offshore exploration test in the Beaufort Sea (U.S.). Only the Tunalik, 20,335 ft, and Inigok, 20,102 ft, wells in NPRA are deeper tests on the North Slope.

There were no drill stem tests (DST). However, the mudlog shows several minor gas kicks. In addition, there were also several descriptions in the mud log of oil-stained sandstones and tar.

Geochemical analyses and lithological descriptions are from cuttings and sidewall cores. The single core that was taken recovered thin-to-laminated, interbedded siltstone, sandstone and shale lithologies.

Plate 1 shows the Gamma, Caliper, SFL, Calibrated Sonic, and Litho Density log-representations at reduced scale. Interpretations with accompanying verbiage are based on the 2-inch suite of logs and include references to sonic shear, ILM and ILD curves, which I am unable to present in this format. *Plate 2* shows a lithologic column based on selected cuttings and electric log intepretation and a column based on only the mud log description. It also shows representative dipmeter rose diagrams. *Plate 3* shows the geochemical data (TOC, %Ro, G.P., P.I., HI, OI, TAI, Wetness, and Kerogen type) plotted vs. depth.

The well log interpretation and geochemical analyses show there are some significant differences between the stratigraphy identified from wells west of ANWR. Nevertheless, there are several similarities of local and regional importance and interest. This report interprets these similarities and differences, and explains how they affect the geology interpolated to exist in the 1002 area subsurface. Paleontological data were not released with the logs and the geochemical data. Consequently, ages assigned to the different units are derived from analogies to units where age-data are available.

The Aurora exploration well penetrated an entirely clastic sequence consisting predominantly of silty shales, or unconsolidated claystone, with a few thin and interbedded sandstone or siltstone units. Two significantly thick sandstone or composite-sandstone units were drilled. This report assigns each of them an informal name, and describes their log and gross compositional features. I compare these Aurora sandstones to equivalent units in northeast Alaska. Both of these sandstones were deeper than any currently successful exploration target on the NorthSlope.

2. Barrow Arch and Breakup Sequence

The Barrow Arch and the Colville Trough are two of the major tectonic elements of the North Slope (Grantz and May, 1983). The Barrow Arch and Breakup sequence rocks are interrelated, comprising a regional event in northernmost Alaska. *Table 1* summarizes some of the nomenclature which has evolved from the analyses of exploration data. In the context of Breakup sequence tectonics, the Barrow Arch is not a single feature. Rather it is a linear series of separate structural highs which shed the Breakup sequence sediments during separate and mostly discrete episodes. Rift sediments shed to the north filled grabens which are now deeply buried and yet untested by drilling. Drilling shows that sediments shed to the south around the uplifts reflect the complex local tectonics and accompanying sedimentation (Hubbard and others, 1987). Petrological differences between these various Breakup sequence sands may reflect the unique sources of the bedrock provenance. Note that there are multiple minor unconformities within the Breakup sequence that accompany the local uplifts. There are distinct pulses of coarse grained sediments, also with minor and local unconformities, that interfinger with basinal sediments of the Colville Trough. The unconformity picked at 17,325 is the most dramatic of these unconformities at the Aurora location.

Brookian sediments represent at least three distinct pulses of sedimentation resulting from the uplifts of the Brooks Range (Hubbard and others, 1987). These are southerly derived sediments that filled the Colville Trough, eventually overstepped the Barrow Arch and proceeded to deposit onto the Beaufort shelf (*Figure 3).*

3. Stratigraphy and Log Analysis of the Sedimentary Units

Unit I

The deepest unit penetrated, 18,325 to 17,325, consists of light-to-dark gray and dark, grayish-brown, splintery to fissile, hard shale and minor amounts of fine to medium grained, white to milky, mostly subrounded, quartzose sandstones. These lithologies are interbedded with distinct sandstone beds comprising less than 10 percent of the unit. The sandstones are less than 5 ft thick, are widely spaced and are not agglomerated into thick units.

Drilling rates were slowest through this interval with an average of 3 or 4 ft/hour. Mudweight averaged 16.0-16.4 lbs/gal. Densities varied widely, 2.50± g/cc. The dipmeter logs from the upper part of this section indicate transport direction varying from NW-NE *(plates 2 and 3).*

Overall, this unit has the highest/hottest average gamma-ray log, 75-105 API units. The variable log pattern suggests a predominantly shale lithology with thin and interbedded sandstones. The re-

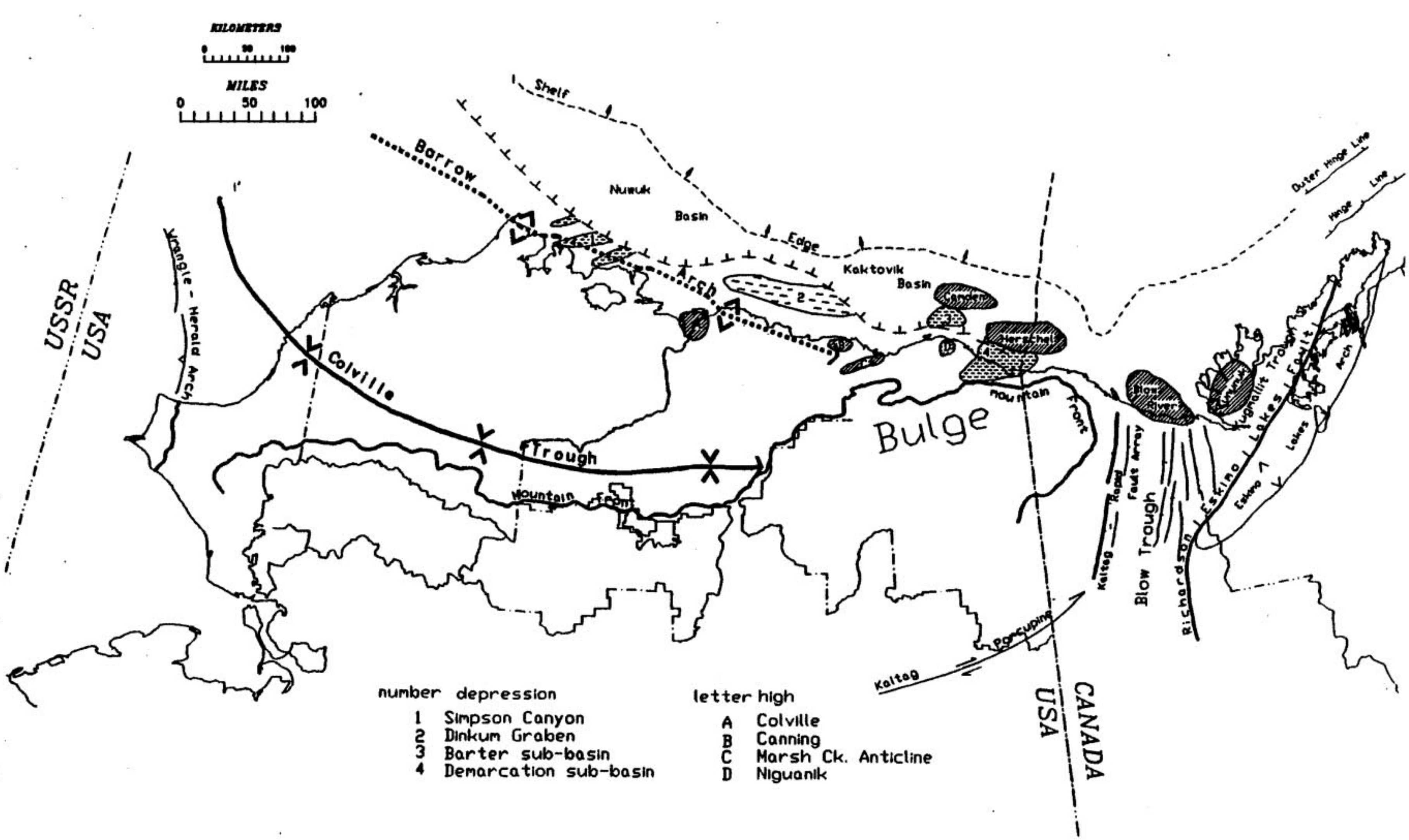

Figure 3
Major tectonic features of the Arctic

Table 1.

A brief synopsis of nomenclature used for rifting-related sandstones and shales encountered along the Barrow Arch.

sequence	investigators	comments
Barrovian	Carman and Hardwick,	infra-rift and rift sediments from a northern source 4 distinct depositional units 2 limited areal extents; ~ 1,500 km2 active reservoir area multiple sand bodies
Rift	Craig and others, 1985	clastics shed into infra-rift basins like Dinkum Graben. may be very thick related to locality and time intervals does not include Barrovian sediments
Beaufortian	Hubbard and others, 1986-1987	rift event sedimentation includes all clastics on Arch, Jurassic - mid Cretaceous northern source, with multiple uplifts transitional basin geometry rifting younger to east
Breakup	Banet, 1990	rift event sedimentation from multiple local uplifts along arch axis separated geographically and temporally unique sand petrologies reflect basement lithologies

sistivity curves show minimal separation because of limited invasion of drilling fluids, suggesting low permeabilities. The sonic curves are variable, Delta t (DT) is 90 ±10 microseconds/ft (μsec/ft) and the Delta t shear (DTs) is 170 ± 15 μsec/ft *(Plate 1)*. The decrease of interval velocity from the bottom part of the unit suggests that there is overpressuring occurring below approximately 17,950.

TOC mostly ranges in value between 1 percent and 2 percent. Kerogens are predominantly amorphous or unstructured. (Amorphous kerogen is the most abundant type reported in the kerogen descriptions throughout all the cuttings samples. However, rather than representing a noncellulosic and possibly productive sapropelic kerogen, the amorphous kerogen in these cuttings is more likely particularly fine-grained and recycled organic material. This is noted as such in all of the log units and, in more detail in another report (Banet, in-progress) on the Aurora well geochemistry. Identifiable Inertinite and Vitrinite macerals comprise only a small fraction of the indigenous organic material. Also, thermal maturity is beyond the catagenesis zone *(Plate 3 and Figure 4)*. As a result, no oil shows would be expected through the basal interval. None were found and only a minor show of gas from a thin sandstone unit was recorded *(Plate 2)*.

The upper contact is picked at top of the interbedded shales and sands at 17,325. Unit I is overlain by a shaly unit which is the base of a coarsening-upwards sequence. The gamma and electric logs show this contact abruptly, and there is a slight change (decreases upsection) in interval velocity on the sonic logs *(Plate 1 and Figure 5)*. The abruptness of the change in the log character, lithology and depositional directions suggests the presence of a major disconformity or an unconformity at the top of the basal section.

Table 2 shows that the interval velocities in this lowest unit most closely match the Kingak Shale (Jurassic lower Cretaceous). Both the Pebble Shale and upper Cretaceous shales have somewhat similar interval velocities. However, Unit I is more than 1000 ft thick, which is substanstially greater than the Pebble Shale. Also, it has a different lithology and log character than the Pebble Shale typically has on North Slope logs. In addition this unit does not have the very distinctive smectitic or interbedded paper/cardboard shale and bentonitic lithology of the upper Cretaceous shales in this region. Without the benefit of the paleontological data to aid the analysis, the interval velocity, lithology and thickness fit no interpretation better than assigning this basal unit as the Kingak Shale. Thus the unconformity at the top of this section is interpreted to be the lower Cretaceous unconformity (LCU) as per the terminology used on the North Slope (Craig and others, 1987; Hubbard and others, 1987; and Banet, 1990).

The presence of the Kingak Shale at this location has important ramifications for the subsurface stratigraphy of this area. The representative nearest well control, shows that the Kingak and older sediments have been eroded from along the Barrow Arch to the west. The Kingak is mostly eroded at the Beli # 1 well and is entirely eroded at the Pt. Thomson-

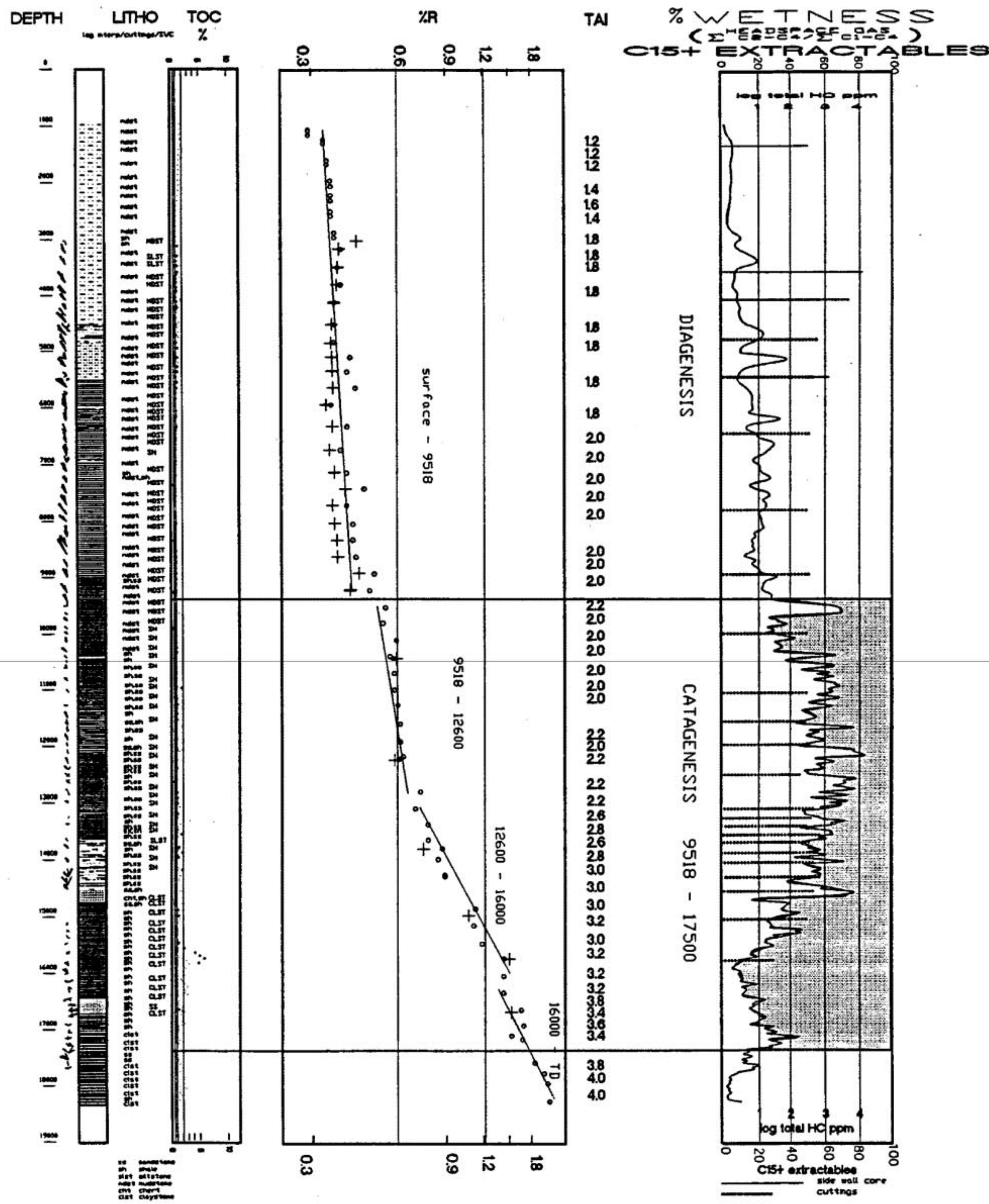

Figure 4
Organic richness and thermal maturity showing TOC, %Ro, TAI, C15+ extractables and gas wetness

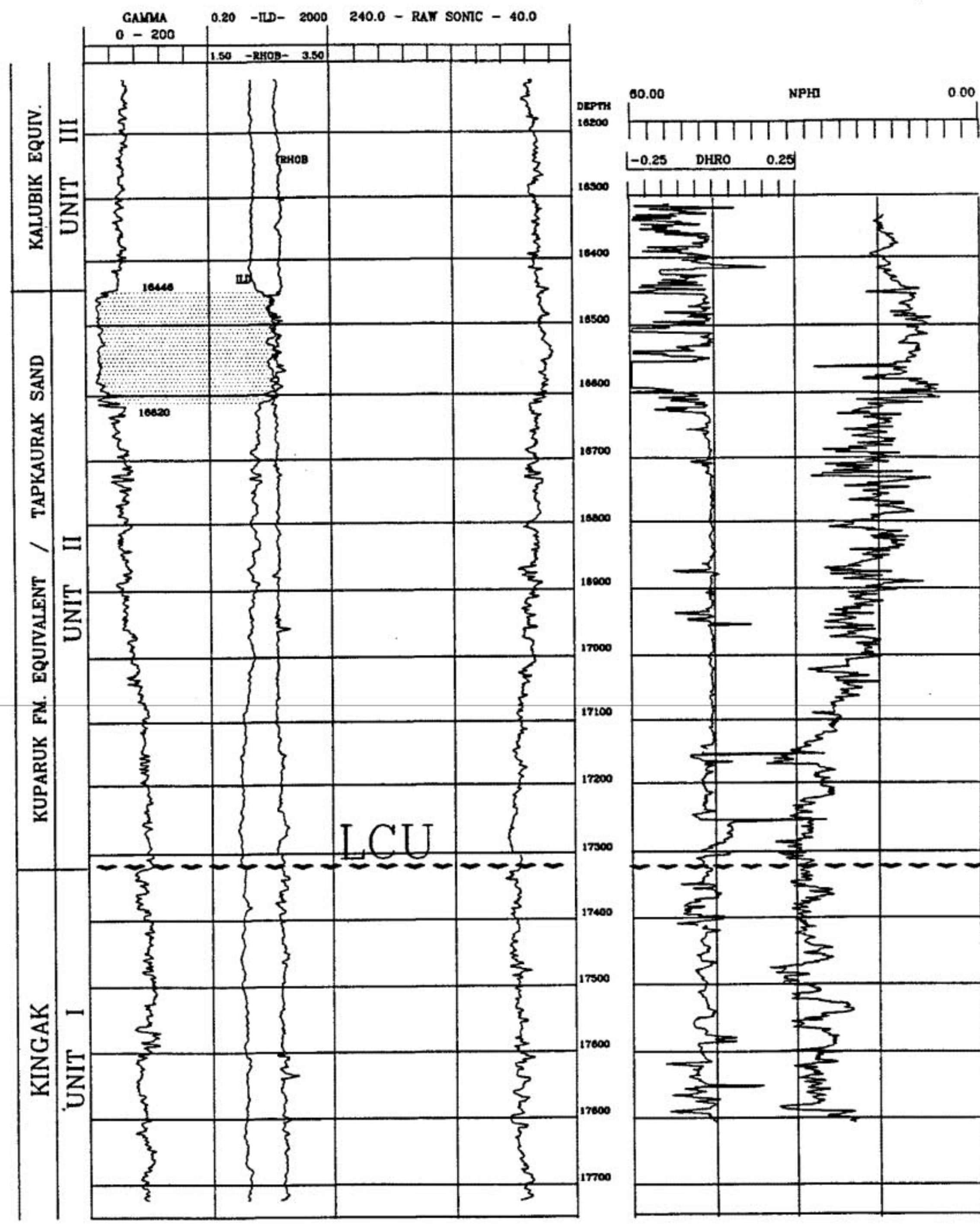

Figure 5
Geophysical logs through the upper Kingak, LCU, Units II and III, with emphasis on Tapkaurak sandstone

Table 2.

Formation velocities derived from analyis of acoustic logs from wells adjacent to ANWR 1002 area (Modified from Foland and Lalla, 1987).

(sigma = velocity difference at 1 STD)

WELL	TOTAL DEPTH
Alaska State A-1	14206
West Staines State #2	13171
West Staines State 18-9-23	13329
Canning River Unit A-1	08874
Canning River Unit B-1	10803
E de K Leffingwell	14804
Beli Unit - 1	14632
Kavik Unit - 1	09550
Kavik Unit - 2	07500
Kavik Unit - 3	05800

Wells used in determining formation velocities in ANWR 1002 area analysis

STRATIGRAPHIC UNIT	VELOCITY (ft/sec)	sigma (ft/sec)	# of wells
Sagavanirktok	8668	534	4
Upper Cretaceous Shales	12010	655	11
Pebble Shale	11120	1029	10
Kemik sand	13608	1689	7
Kingak Shale	10626	1053	5
Sag River sand	13683	1185	6
Shublik	15544	769	5
Ivishak/Prudhoe sand	14749	728	5
Kavik Shale	13927	204	3
Echooka sand	14933	1650	2
Sadlerochit Gp. undif.	14680	354	2
Lisburne Gp. carbonate	19709	1247	6
Endicott Gp. non coal	15308	0	1
pre-Mississippian (carbonates)	21740	0	1
pre-Mississippian (argillite)	15382	675	4

Flaxman Island, West Staines wells and from some locations along the north side of the Sadlerochit Mountains*(Figure 2)*. From these observations, Bird and Molenaar (1987) suggested that the Ellesmerian section is absent beneath much the Coastal Plain of northeast Alaska.

By contrast, the Kingak and Ellesmerian section are exposed along the mountain front, immediately south of the 1002 area. There is also an allocthonous exposure of Kingak on the 1002 area of the coastal plain. In North Slope stratigraphy, undisturbed by faulting or truncation, the Ellesmerian sequences (upper Mississippian - Triassic) are unconformably overlain by the Kingak Shale of the Breakup sequence (Hubbard and others, 1987, Banet, 1990). Of the more than 2500 wells drilled on the North Slope, only around Barrow do Avak and South Barrow #5 wells go from Kingak into pre-Ellesmerian basement (Bird, 1988).

Admittedly there are some wells that encountered less than 200 ft of Kingak above basement, or had only relatively thin and partial Ellesmerian sections beneath the Kingak. However, these wells, like Avak and So. Barrow #5 are around Barrow which is the westernmost and structurally highest part of the Arch. With faulting and truncation along the Arch, Brookian sediments are documented to unconformably overlie both the pre-Ellesmerian and Ellesmerian sequences. But, where the Kingak is encountered, so too is the Ellesmerian. Thus, the presence of Kingak at Aurora suggests some of the Ellesmerian formations may be present in the large seismically mapped structures in ANWR unless there is a major here-to-for undocumented change to the regional geology.

Consequently, the Prudhoe area reservoirs (Lisburne Group, Sadlerochit Group, Shublik Formation and Sag River/Karen Creek sandstone (Jamison and others, 1980)) could also be considered prospective (to have potential) in the large seismically mapped structures of the eastern 1002 area. Kelley and Determan (1989) initially proposed the existence of Ellesmerian reservoirs within the 1002 area based on field relationships and structural restorations of the LCU and older section around the east end of the Sadlerochit Mountains. Even the initial ANWR assessments Grantz and Mull, 1978; and Mast and others, (1980) stressed the magnitude of importance of having Ellesmerian reservoirs in the 1002 area.

Unit II

Unit II is from the LCU at 17,325 to 16,446. It is shaly at the base, becoming an interbedded and coarsening upwards sequence of sandstones or siltstones and shale *(Figure 5)*. The upper and lower contacts are distinct on all the logs *(Plate 1)*. The shales are mostly dark gray to black, very silty, fissile to blocky, somewhat hard, pyritic and micaceous. The sandstones are fine- to coarse-grained, and quartzose. They are thin and wide-spaced at the base, becoming very thick at the top of the unit. The interval between 16,620 to 16,446 is a well-defined massive sandstone with only 8 ft of shale partings *(Figure 5)*. This sandstone has minor amounts of tan, dolomitic cement. In the cuttings samples, quartz grains are fine to coarse, subangular to subrounded and clear to milky or white. Also, there are minor amounts of black chert, biotite (which is very likely a remnant from the drilling additives), and trace amounts of both igneous rock fragments and volcanic rock fragments (possibly plagioclase).

The gamma-ray log decreases consistently upsection to the base of the massive sandstone from about 75 to 40 API units. Through the sand, the gamma curve is very low indicating that the sand is relatively free of clay minerals. The ILD curves also separate through the sandstone unit, suggesting some invasion of drilling fluids and permeability. The DT runs about 70 µsec/ft, dropping to approximately 60 µsec/ft, through the sandstone *(Figure 5)*. The DTs is about 130 µsec/ft, dropping to 110 µsec/ft through the massive sandstone. This (DTs) is a distinct log pick, perhaps as a result of the increased sand content of the section or less severe burial affects than in the underlying Kingak Shale. The dipmeter shows preference for predominantly easterly sediment transport direction with NNE and SE minor components *(Plate 2)*. Drilling rates were mostly 4 ft/hr and up to 6 ft/hr through the massive sandstone. Grain densities are similar to those in the underlying Kingak formation, about 2.60 g/cc.

Organic carbon richness is distinctively higher in Unit II than in the Kingak. TOC averages about 2 percent. Kerogen analyses show some Vitrinite maceral in addition to the Inertinite and the amorphous material. Thermal maturity indicators *(Plate 3 and Figure 4)* put unit II in the high end of the catagenetic zone. These maturity values are closely related to the maturities of the underlying unit. There were no reported shows of hydrocarbons. However, this was not unexpected because the pyrolysis data indicates that the indigenous kerogens are very lean. The unit is at the advanced stages of catagenesis *(Plate 3)*.

Stratigraphic position atop the Kingak Shale indicates/suggests that Unit II is equivalent and possibly coeval to Detterman and others' (1975) Kongakut Formation or its Pebble Shale and Kemik units. These lower Cretaceous units are commonly identified across the North Slope mountain front and in Coastal Plain subsurface stratigraphy. The Kemik and Pebble Shale are part of the Breakup sequence along the coast (Banet, 1990), but they contain Brookian depositional elements where found further south as at Detterman and other's (1975) type section.

At Aurora, Unit II's interval velocity, the pyrite in the lithology, TOC content, and thickness of the section fit well with the Pebble Shale unit (Hauterivian - Valanginian) described from both outcrops and well data. However, the Pebble Shale typically has a distinctive, high gamma-ray horizon at the top and floating pebbles, cobbles or frosted quartz grains. It unconformably overlies the Kingak Shale or the Kemik sandstone where the Kemik is present. This is not quite the same stratigraphy as at Aurora *(Plate 3 and Figure 5)*. Outcrop descriptions of the basal clay-shale member of the Kongakut, which underlies the Brookian Kemik, do not match well with the lower part of Unit II's lithology at Aurora so it is not considered to be equivalent.

Tapkaurak Sand

I suggest that the massive sandstone between 16,620 to 16,446, be referred to as the Tapkaurak sand to facilitate its comparison to other Breakup sequence sands. The Tapkaurak has common to abundant clear quartz grains and minor amounts of biotite (?), igneous rock fragments which suggest a provenance different from that seen from the typical Kemik exposed in northeast Alaska (Mull, 1987).

Kemik Sand

The Kemik (Hauterivian) is a horizon of discontinuous sandstone bodies. They typically have barrier island geometry where the individual sands are generally about 4 miles X 6 miles. At nearest outcrops it is up to approximately 150 feet thick. The lithology is petrologically mature like the Ellesmerian clastics. It is typically quartzose, mostly fine-grained sandstone, with minor stringers of chert-pebble conglomerate, ripple marks and clamshell impressions. The Kemik is found in wells west of the 1002 area approximately 90 miles away, and at allochthonous outcrops around the Sadlerochit mountains 60 miles to the southwest *(Figure 2)*.

Pt. Thomson Sand

The Pt. Thomson sandstone is another coeval (or nearly so) lower Cretaceous unit. It is a Breakup sequence sand of limited lateral extent located only 90 miles to the west of Aurora well (perhaps even closer, if it extends into the 1002 area). Unlike the Kemik sand, the Pt. Thomson sands rests directly upon basement rocks which are comprised of argillites, carbonates, phyllites and clastics; lithologies commonly associated with the Neruokpuk Group.

The Pt. Thomson sands and conglomerates are comprised of a high percentage of large and angular carbonate rock fragments, boulders and lesser amounts of argillite. Gautier (1987) reports detrital dolomite grains 53 percent, quartz grains 36 percent and metamorphic and sedimentary rock fragments 11 percent. This mineralogy, the angular grain shapes, and size distribution indicate that the Pt. Thomson sands have been deposited near their source - a local uplift. However, most of the lithology, the thickness and the depositional mode of the Tapkaurak sand more closely resembles the Kemik rather than the Pt. Thomson *(Table 3)*.

It is apparent that the shale and Tapkaurak sand sections of Unit II are more closely related than the Pebble Shale and Kemik sand where they are typically seen along the mountain front and in the nearest Coastal Plain wells *(Figure 2)*. The coarsening- and thickening-upwards section shows a steadily increasing higher energy depositional environment, from initally quiescent marine conditions. In addition, the geographical relationship between the marine Unit II and the mostly nonmarine Pt. Thomson sand is similar to other Breakup sequence sandstones, such as the Kuparuk and Put River sands which are identified further west (*Table 3*).

Table 3

A comparison of lower Cretaceous sands and shales from northern Alaska

HRZ AT KUPARUK	PEBBLE SHALE	KONGAKUT FM.	ARCTIC CK.	AURORA UNIT III
4 – 9 %TOC shale w/ paper fissility ~200' Albian – Aptian	GRZ LCU basal unconformity No. Slope regional silty shale black, fissile, pyritic minor bentonite 200 ft. to 300 ft. floating pebbles/grains rich source rock TOC to ~ 5% Haut. to Barr. BREAKUP SEQUENCE	sh, slst, minor ss 4 members deep water turbidite ~ 1900 ft. thick internal unconformities GRZ in Pebble Sh. black, manganiferous few fossils floating chert pebbles Kemik sand ~ 260 ft. quartz arenite to– feldspathic wacke very fine–grained basal contact conformable Berriasian – Barremian BROOKIAN	ss & sh vf. to fine grained quartzose 5 ft. to 90 ft. beds ~ 250 ft. total sand thins eastward siliceous, hard 100% recrystallized deep marine & turbidites flutes, grooves & load casts blk. fissile shale minor bentonites Albian Aptian BROOKIAN	LTU at top sh, slst & carb sh gray to dk. gray very thin beds very silty cuttings 500 ft. ~SE–NW transport lean source rock lower – mid Cretaceous BREAKUP SEQUENCE
KALUBIK FORMATION below HRZ– 150 API internal, local HRZ overlies Kuparuk sands mudst & slst carbonaceous moderately fissile pyritic & sideritic 200 ft. to 300 ft. marine deposition Barremian – Aptian BREAKUP SEQUENCE				
KUPARUK	**KEMIK**		**POINT THOMSON**	**AURORA UNIT II**
below GRZ multiple beds sand & shale shallow marine fine–grained, rounded glauconitic, sorted intraformational unconformities distinct contacts areally limited unit ~ 5 mi. X ~15 mi. Haut. – Barr. oil & dissolved gas BREAKUP SEQUENCE	below GRZ LCU basal unconformity sands to ~ 150 ft. sand & shale distinct to interbedded fine–grained, rounded well sorted, marine No. Slope Regional ~6mi.X 24mi. units northeast trend commonly imbricated mega–fossils Hauterivian gas BREAKUP SEQUENCE		below GRZ LCU basal unconformity thick single unit sand, conglomerate, breccia angular dolostone fragments sits on basement poorly to well sorted nonmarine limited lateral extent ~ 3mi X 5mi east–southeast trend? distinct contacts barren of fuana oil & condensate BREAKUP SEQUENCE	no GRZ LCU at base distinct contacts interbedded ss & sh coarsens & thickens upwards 174 ft. massive sand at top Tapkaurak sand fine to coarse–grained clear to white grains subrounded/subangular dolomitic cement unconsol. to med. hard BREAKUP SEQUENCE

Key:

- GRZ gamma ray zone
- HRZ highly radioactive zone
- LCU lower Cretaceous unconformity
- LTU lower Tertiary unconformity

Stratigraphic position and geography emphasized. Some age relationships uncertain.

Unit III

The logs show Unit III quite distinctly, with contacts at 16,446 and 15,937. The top is picked at the dramatic log break on the sonic log at 15,937. The Gamma log break at 15,950 coincides with the base of casing used to keep the hole open. Logs run before casing (Gamma, ILD, and raw sonic-BHC) show that the log breaks are real however, and not merely artifacts of the casing. (The BHC sonic log shows the depths inaccurately. It is off by some 125 ft at the Tapkuarak sand, and shows the contact shallower than the other logs. For unexplained reasons the calibrated sonic log with gamma, Geogram, ILD and RHOB start at a total depth 18,200 instead of 18,325. This offsets all the log picks upsection, but no mention is made of the fact anywhere in the log package or assosciated correspondence. The Array Sonic - STC processed log with Gamma shows depths accurately, but was only logged to 18,137.)

The dramatic change in the logs at 15,937 showing changes in lithology and transport direction suggests that the upper contact marks a major unconformity or disconformity, or shale on shale hiatus. The mudlog changes from a mostly brown to dark-gray, laminated shale at the top of unit III to a dark gray blocky shale above *(Plate 2)*.

The logs show that unit III is almost entirely shale. This shale is dark brown to dark-gray, with minor carbonaceous laminations, and traces of siltstone. A few light to dark-gray and brown siltstones appear as rare, wide spaced, thin (less than about 1 foot thick), stringers. The gamma log shows a shaly sequence that increases steadily upsection from 60 to 90 API units, contact to contact. The resistivity also shows a shaly sequence with a few widespread discernable sandstones or siltstones. The sonic logs run DT 65-70 μsec/ft and DTs varies 110 to 130 ± 10 μsec/ft. Transport directions from the dipmeter show little magnitude and little preferred direction of orientation, except near the upper contact where NNW is preferred (Plate 3). Mud weight runs 16.0 lbs/gal and drilling rates were 4 to 6 ft/hr.

The geochemical profile *(Plate 3)* shows average TOC's between 2 to 3 percent from cuttings and about a percent less from sidewall core analyses *(Figure 4)*. Likely there is considerable sloughing of upsection material, or the shale and siltstones were not sampled representatively by the sidewall cores. The thermal maturity indicators show that Unit III is within the catagenetic zone *(Figure 4, and Plate 3)*. Consequently there should be some generation of hydrocarbons but pyrolysis data and gas wetness are both anomalously low. This may be due, in part, to unusually gas prone Vitrinite identified in the section, or that the lean nature of indigenous kerogens is due to reworked and recycled organic material *(Plate 3)*. Overall, these are very lean values for these levels of TOC at this level of catagenesis. Only a minor gas show was reported at base of the casing at 15,950.

The stratigraphic position of Unit III atop the Tapkaurak sandstone, its thickness and interval velocity match well with the Pebble Shale unit. However, the lithologic description lacks the pyrite, the minor amounts of bentonite, the floating sand grains and pebbles that are common in the Pebble shale. Also, this silty shale is not distinctively radioactive nor is the TOC content unusually high. Unit III represents a more open marine and oxidizing environment than is usually envisioned for the Pebble Shale unit. The log contacts at 15,937, the change of lithology and the direction of sediment transport suggest that there is an unconformity. This analysis supports that Unit III is related more to Unit II and the Breakup sequence rather than to the overlying unit. Thus, by analogy to other Breakup sequence units it is probably lower to possibly mid-Cretaceous age.

Unit III has no resemblance to the possibly coeval lower Brookian sequence Arctic Creek facies, even as a distal equivalent *(Table 3)*. The Arctic Creek unit is an Albian-Aptian age, interbedded chert-litharenite and shale, with markedly north-directed sediment transport directions (outcrop measurements) from immediately south of the 1002 area. Although Unit III has variable transport directions, it shares important lithological and log charcteristics with the underlying Unit II.

Comparison to Ugnuravik Group

Units II and III together, closely resemble the Kuparuk (Hauterivian - Barremian) and Kalubik (Barremian - Aptian) Formations of the Ugnuravik Group described by Carman and Hardwick (1983) *(Figure 6)*. Immediately west of Prudhoe, the Kuparuk Formation consists of up to four cyclic sequences of coarse and fine-grained terriginous to shallow marine, sandstones, siltstones and mudstones. Glauconite can be abundant. Total thickness is up to about 350 ft. Individual sandstones are generally less than 25 ft thick, but are commonly amalgamated into thicker bodies. The sandstones have both lense and lobate geometries, and intra-formational unconformities are common (Carman and Hardwick, 1983).

The overlying Kalubik Formation is some 200 to 300 ft of brownish gray to black, carbonaceous, silty, marine mudstone. There is a thin, high gamma ray zone, sideritic mudstone reported within the Kalubik. The basal contact is commonly gradational, and the top is picked beneath the High Radioactive Zone (HRZ). The HRZ is a marginal marine to deep-water gray to black mudstone. It has carbonaceous laminations, with paper fissility, shell fragments, quartz, silt and woody fragments. The HRZ also has 4 to 9 percent TOC and it is determined to be Albian - Aptian age in and around the Kuparuk River oil field (Carman and Hardwick, 1983). The Ugnuravik Group is part of the Barrovian depositional sequence. The Barrovian sequence is but one of several localized, nearly coeval, pulses of rift- associated sedimentation which comprise the Breakup sequence.

Lithologies, log characteristics and stratigraphpic position all indicate that Units II and III together correlate closely to the Kuparuk and Kalubik Formations. (There are also some similarities between the lower portion of Unit II, between 17,325 to 17,050 and the basal Miluveach Formation.) The major difference is that there is only one sandstone unit, the Tapkaurak, at the top of Unit II, rather than the stacked sands of the Kuparuk Formation *(Figure 6)*.

At Aurora, thickness, mineralogy, grain size and depositional environment of the Tapkaurak are more similar to the Kemik than to the sandstones of the Kuparuk Formation. But Unit II is only sampled, so far, at a single location. Other differences include that there is no highly radioactive, high TOC zone present at Aurora, and without paleontological data, the existence of minor or local unconformities cannot be documented.

Overall though, the Aurora section represented by Units II and III belongs within the Breakup sequence. Its stratigraphy more closely resembles the Kuparuk and Kalubik Formations than it does the Kongakut, the Coastal Plain Pebble Shale and Kemik, the Pt. Thomson sands, or the Brookian Arctic Creek Facies.

Brookian Sequence

All three Brookian sequences are present in northeastern Alaska. The lower Brookian Arctic Creek facies, described earlier, is present at outcrops 35 to 50 miles south and southwest of Aurora. Middle Brookian rocks are predominantly marine facies consisting of mostly incompetent, gray, smectitic shales with thin interbedded sandstones, or banded, bentonitic, organic-rich shales (Colville Group Shale and Bentonitic Shale unit, Banet, 1990) in the western and northern parts of the 1002 area. In addition to these shales, there are the interbedded, black, hard, fissles shales and mostly indurated sandstones and conglomerates of the Sabbath Creek unit (Buckingham's (1987) Jago Formation) which crop out on allochthons in the south-central part of the Coastal Plain.

Upper Brookian nonmarine facies are the Sagavanirktok Formation (Detterman and others, 1975). Nearby wells and outcrops across the 1002 area show that the Sagavanirktok lithologies are composed of up to 8,800 ft. of unconsolidated sands, silts, and clays with both pebble conglomerates and floating-pebble zones and pieces of partially coalified wood. Oil stained sands and silts are common.

Figure 3 shows that the Aurora location is along the trend of the Hinge Line, where basement rocks are normal faulted (mostly down-to-north) to great depths beneath some 35,000 feet of sediments. The Barter and Demarcation sub-basins are juxtaposed to this position. Both sub-basins may have over 20,000 feet of upper Brookian (Oligocene and younger) shelf or deltaic sediments which correlate to the Sagavanirktok Formation, onshore. These Upper Brookian sediments are upturned and truncated at their basin margins by a ridge which separates the sub-basins. The core of this ridge is composed of older, uplifted Paleocene (?) to Eocene, middle Brookian marine shales (the mobile shales) and silts (Grantz and May, 1982, and Craig and others, 1985). The ridge separating the sub-basins has a comparatively thin veneer of upper Brookian rocks upon the thick, structurally deformed middle Brookian sequence (e.g. fig. 30 in Craig and others, 1985: or figs. 16 and 17 in Banet, 1990).

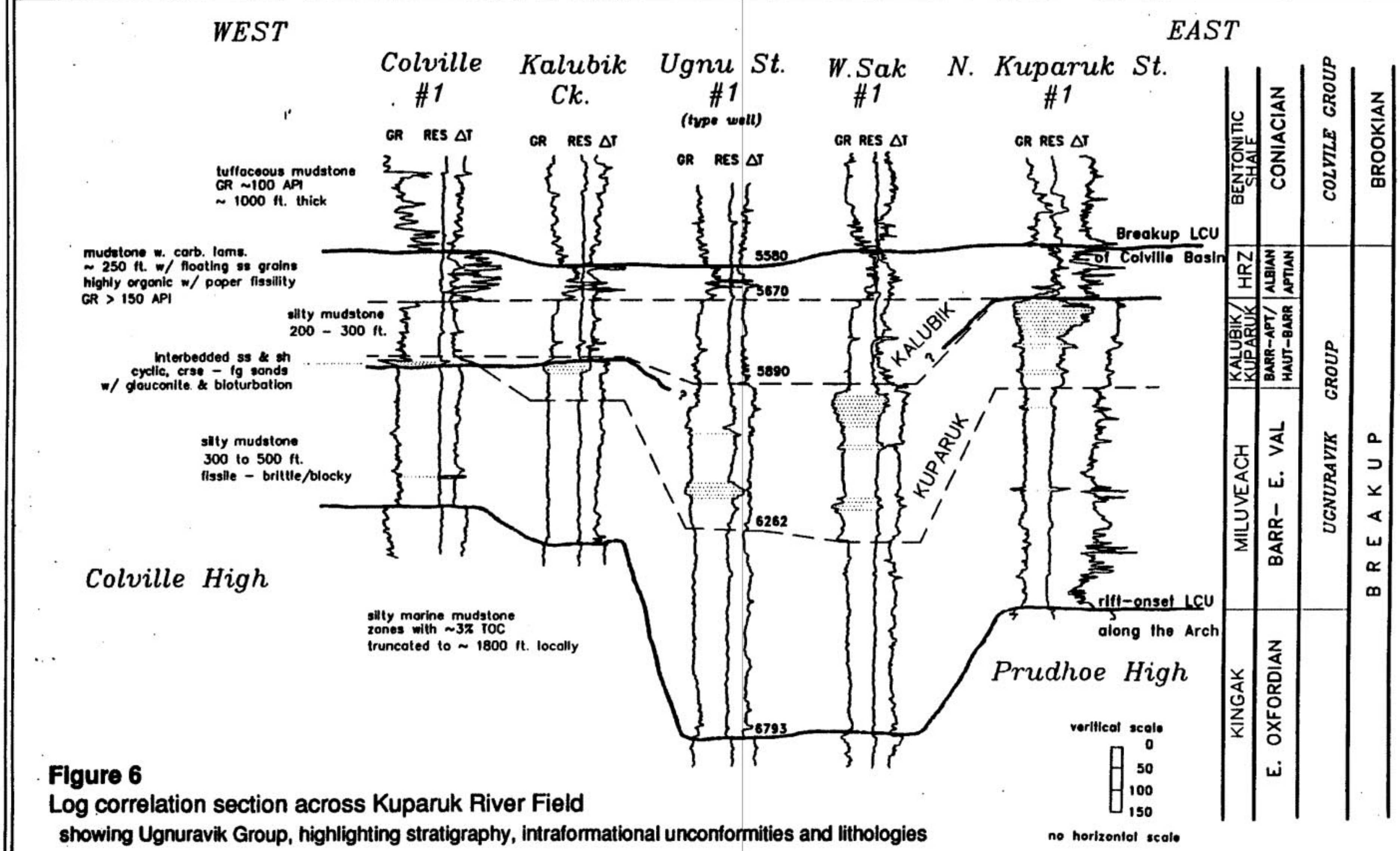

Figure 6
Log correlation section across Kuparuk River Field
showing Ugnuravik Group, highlighting stratigraphy, intraformational unconformities and lithologies

(modified from Carman and Hardwick, 1983)

Key: unit contacts - - - - - unconformities

The presence of Brookian Sequence rocks at this well interval is determined from the interpretation that the LCU is identified from log breaks at 17,325. Similarly, the dramatic log break at 15,937, the lithological change and the different sediment transport directions also suggest a major disconformity or unconformity at the top of the Breakup sequence. This stratigraphic relationship is analagous to the Pt. Thomson-Flaxman area, where Breakup sequence sands and shales are terminated by a lower Tertiary unconformity (LTU) (Craig and others, 1985) and are overlain by Brookian sediments. The lower Tertiary unconformity cuts down-section eliminating the entire Breakup sequence from the northern part of the Pt. Thomson area *(Figure 7)*. By analogy, the unconformity at 15,937 in Aurora will be referred to as the LTU also.

Well and outcrop data from northeast Alaska indicate that the Bentonitic Shale unit is the distal member of the middle Brookian sequence (Hubbard and others, 1987). As at the Pt. Thomson area, the upper Cretaceous Bentonitic Shale unit is absent at Aurora either from nondeposition or erosion by the LTU at 15,937. The Bentonitic Shale unit is a distinct widespread lithology. Molenaar (1983) and Molenaar and Bird (1987), refer to this as the upper part of the Hue Shale Unit. The Bentonitic Shale extends from the Pt. Thomson-Flaxman area across northeastern Alaska and into the Tuktoyaktuk Pennisula area of Canada. It is a black, laminated shale with paper to cardboard fissility, interbedded with cream-colored to yellow- stained bentonites ranging in thickness from laminations to about 3 ft. In addition, it is a very organic-rich, potential source rock with TOC's as high as 14 percent. Gamma-ray logs through this shale typically exceed 150API units. The Bentonitic Shale ranges in age from at least Albian to Coniacian (Banet, 1990). The Bentonitic Shale crops out across much of the 1002 area, including the Coastal Plain, and as close as 15 miles south of the Aurora location. Its absence at Aurora is conspicuous, but regional considerations suggest that petroleum potential of the area is probably not compromised, significantly. Consequently, the section at Aurora is considered to be all Tertiary age.

Tertiary

The Tertiary section at Aurora well is a very thick sequence of predominantly shales and siltstones with a few sandstones. It is comprised of 11 units (IV through XIV) that are separated mostly by their log characteristics and, to a lesser extent, by their geochemical data. Some of the differentiations are subtle, with interpretations based upon changes in grain size trends, e.g. a coarsening upwards sequence of mostly shale to silt lying upon another coarsening upwards sequence also comprised of shale and silt. Log character changes suggest that there is an unconformity at 2,385. Lithological changes indicate that the shallowest section likely belongs to a different depositional sequence. There is no paleontological data publicly available at this time so the middle Brookian section is shown as ranging from Paleocene through Eocene while the upper Brookan section is shown as ranging from Oligocene to Pliocene. The Oruktalik sand correlates to the Paleocene age sands at the Pt. Thomson-

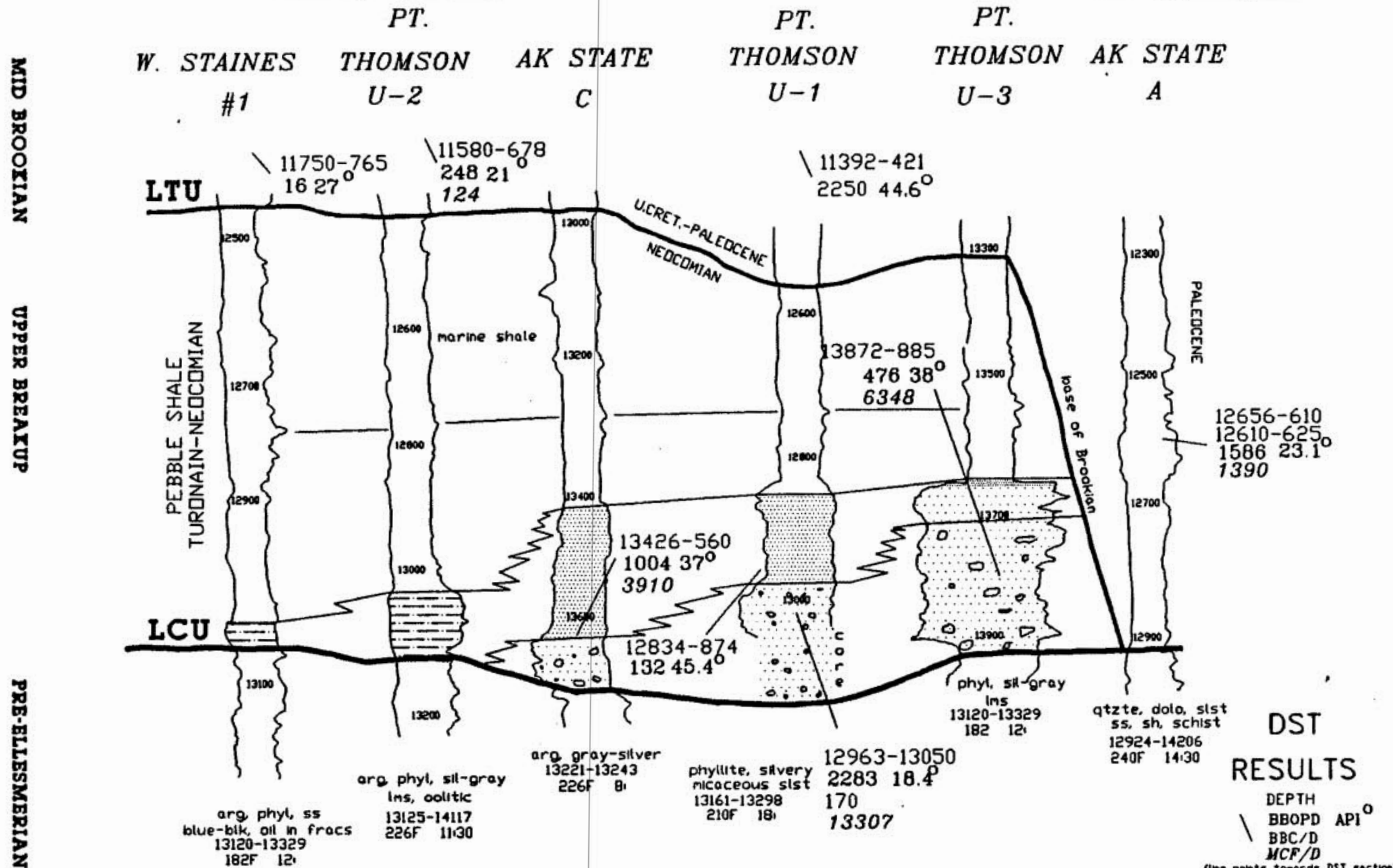

Figure 7
Well correlation section through Pt. Thomson-Flaxman area
showing DST's from Thomson and Flaxman sands, and basement rock data

(oil in BOPD, condensate in BBC/D and gas in MCF/D; modified from Craig and others)

basement rock data: lithologies, depths, BHT's and hours since circulation ceased

Thomson-Flaxman Island area.

The overall lack of major variation throughout the Tertiary age rocks (Units IV throught XIII) suggest that these sediments are mostly part of the same depositional sequence. These lithologies represent mostly marine shelf depositional environments like the middle Brookian sediments onshore. Thus, barring a major change in the depositional stratigraphy and the tectonic framework along the Hinge Line, the Tertiary rocks at Aurora are considered part of the middle Brookian sequence. Consequently they are Paleocene to Eocene age. The shallowest unit, XIV, then is part of the upper Brookian sequence and Oligocene, or younger.

Unit IV

Unit IV, 15,937 to 13,725, is an overall coarsening upwards sequence composed of predominantly shale intervals, stacked sandstone units and interbedded sandstones and shales. The base is the LTU at 15,937 where the blocky, gray to black, silty shales unconformably overlie the brown, laminated carbonaceous shales and siltstones of unit III. Possibly proximal equivalent and perhaps coeval units in ANWR, about 25 miles to the south, are predominantly cobble to boulder conglomerates and interbedded black shales (Buckingham, 1987; and Detterman and Spicer, 1981). Outcrop measurements of this thick section of Paleocene age conglomerates, sandstones and shales show exclusively northward transport. The lack of coals and the sand casts of trees indicate that deposition was mostly in oxidizing environments. Other possibly coeval rocks in the Edlok N-56 well in the Canadian Beaufort Sea, about 65 miles southeast, are also thick to massive bedded sandstones and shales.

The basal portion of Unit IV, 15,937 to 14,828 is mostly shale with a few distinct sandstones. The shale is gray to dark gray or brown. It is hard, usually very silty, slightly fissile, splintery and has traces of pyrite. There are also a few sandstones that are friable, very fine-grained with salt and pepper textures (i.e. approximately equal admixtures of black and white chert fragments with approximately equal grain size).

Oruktalik Sand

The upper portion of Unit IV, 14,828 to 14,685, is 47 percent sandstone in beds that are thick enough to be resolved by the logs (67 ft sands/143 ft unit thickness). Several sands are amalgamated into a single log unit *(Figure 8)*. This sand is called the Oruktalik sand to facilitate comparisons to the other stratigraphically similar sands in the area. It and the Tapkaurak sand are the only notable sands in the entire Aurora well. The individual sandstones of the Oruktalik are thin-to-thick and interbedded with shales. From cuttings samples, the grains are mostly clear or white, fine to coarse-grained with salt and pepper appearance from the black and white chert lithic fragments. The mudlog reports some pebble conglomerate comprised of larger black and white sub-angular chert fragments. These sands are mostly friable with traces of tan dolomitic or siliceous cement. The only significant gas show from the well was reported from this interval.

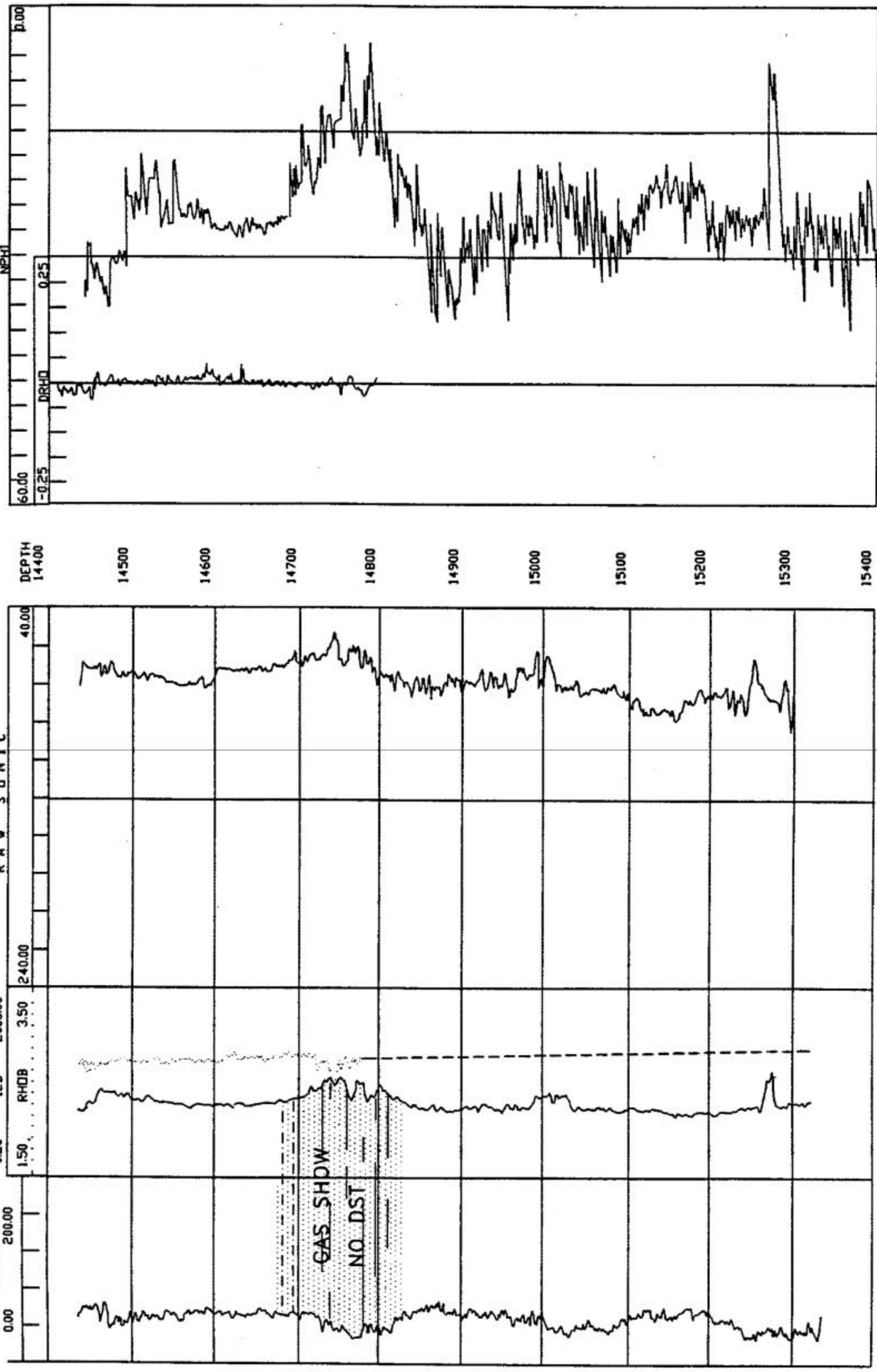

Figure 8
Geophysical logs through log Unit IV

The interval between 14,685 to 14,550 is shale and the remainder of the unit to 13,725 consists of thin, but distinct, sandstone beds and interbedded shale. The shale is silty, blocky and gray to gray-brown at the base, becoming dark brown to black and carbonaceous to more of a siltstone upsection. Sandstones become more numerous, thicker, and more coarse-grained upsection. The sandstones are gray, friable, fine to coarse grained, with angular to subrounded, salt and pepper (black and white) chert and quartz fragments. Near the top of the unit, siltstones and coal complete the lithology. A show of gas was recorded near the top of this section.

The upper and lower contacts are fairly distinct. The gamma and resistivity logs show that the sandstones are thin, but quite distinct where they occur. The section below 14,828 has very few sandstones and the section above has both shale and interbedded sandstone and shale. Despite casing effects and different log runs, the gamma increases overall upsection as does the resistivity. The sonic curves increase from DT 100 ± 10 µsec/ft to 70 ±10 µsec/ft above the casing. DTs varies sharply between about 130-150 µsec/ft. Sonic logs also show low velocities, suggesting overpressure, coincident to the gas shows *(Plate 1).*

Drilling rates were 2 ft/hr near the base and up to 9 ft/hr upsection. Mudweights varied from 13-14 lbs/gal. Sediment transport directions show pronounced NW and NE trends, becoming less developed but more towards NW upsection *(Plate 2).*

Geochemical data shows that this section has approximately 1 percent to 2 percent TOC throughout most of the section. TOCs are up to about 5 percent from sidewall cores in the basal portion of the section. Kerogens are mostly amorphous with minor amounts of Inertinite and Vitrinite macerals. Thermal maturity is within the catagenetic zone, but hydrocarbon indicators are very low; extremely low for the amount, and kind of indigenous organic matter, at this level of maturity. Noticeable exceptions coincide with samples having the higher TOCs (2 to 5 percent).

Flaxman Sands

The Oruktalik sandstone at Aurora shares some important similarities to the sandstones from the Pt. Thomson-Flaxman area that are upsection from the Pt. Thomson sands *(figures 2 and 7).* Bird and Molenaar (1987), Gautier, (1987) and Molenaar and others (1986) refer to these sandstones as turbidites of Paleocene age. I propose calling these sands, which are stratigraphically above the LTU, the Flaxman sands. This should help to differentiate them from the older Breakup sequence Pt. Thomson sands from the same area.

Both the Oruktalik and the Flaxman sands are the first sands of notable thickness, stratigraphically above the LTU. In the wells in which they have been found, the Flaxman sands tested gas, condensate, and oil *(Table 4 and Figure 7).* Abundant oil shows were also noted in some sections though not tested (e.g. Pt. Thomson Unit I). The Flaxman sands are mostly interbedded with shale, as is the Oruktalik sand. However, the Flaxman sand intervals shown on *Table 4*, are 25 percent to 75 percent sand with up to 141 ft total sand thickness. Cuttings lithologies show that the Flaxman sands are mostly gray to black, very fine- to medium grained, moderately to well sorted, and are subangular to subrounded. Gautier (1987) reports 50 to 60 percent monocrystalline quartz. Aurora mudlogs list black and white chert, argillite fragments, siltstone laminations and some coal. Both the Flaxman and Oruktalik sands are friable.

The Flaxman sands have more pronounced basal contacts and the logs typically show more sand development than the Oruktalik sands. In addition, although the Oruktalik sand has some coal and chert fragments, it lacks argillite fragments which may suggest a different sediment source and environment of depostion. Flaxman sand porosities range from 0 to 15 percent (Gautier, 1987). The more deeply buried Oruktalik sand sonic porosities are calculated to be approximately 4 to 10 percent. Whatever the differences between the Flaxman sands and Oruktalik sand though, porosities and permeabilities have not been totally destroyed. In addition a hydrocarbon plumbing system is operating and actively charging (i.e. supplying hydrocarbons to) the sands at both locations.

Unit V

The logs indicate that a predominantly silty shale unit with few distinct sands overlies the interbedded sands and shales of unit IV. Between 13,725 amd 13,252 cuttings lithologies are mostly gray- to brown, clays and siltstone with carbonaceous laminations. Fine grained, gray, salt-and-pepper texture sandstone, gray pyritic silty shale and brittle coal are minor lithologies of this unit.

The basal contact is distinct on logs. Overall, grain size variation is minimal through unit V. DT runs 75-80 µsec/ft. DTs runs from a rather uniform 155 µsec/ft changing to 145 ± µsec/ft at 13,600, and to 160-130 µsec/ft near the upper contact. The dipmeter indicates a NNW-NNE transport direction which is less pronounced than in the underlying Unit IV. Drilling rates varied between 6 to 8 ft/hr, and mud weight was 13 lbs/gal *(plates 1 and 2)*.

Both cuttings and sidewall core TOC's are between 1 and 2 percent. Two cuttings samples have conspicuously high TOC values; one in excess of 5 percent at the upper end of the unit. Kerogens are mostly amorphous with 20 percent Vitrinite and 5 percent to 20 percent Inertinite. Thermal maturity is within the catagenetic zone. The slope of %Ro vs. depth shows that this unit and the more deeply buried units have been subjected to a more severe thermal regime than units upsection. Except for the high TOC samples which have good Genetic potential, hydrocarbon indicators are low. However, gas wetness is about normal for this level of catagenesis *(Plate 3)*. There is a dramatic increase in TAI at about this interval suggesting an unconformity. However the rest of the geochemical data and sonic log data suggest a facies change rather than a significant unconformity at 13,252.

Table 4.
Oil and gas tests from Basement rocks, Breakup sequence and Brookian sands of the Pt. Thomson area.

WELL	INTERVAL (from KB)	GAS MCFD	OIL BOPD	GOR	API degrees
BASEMENT COMPLEX					
Sohio AK Is	114997-15022	2200	175	11270	>40
Exxon AK St F1	13940-14316	2475	152	19572	35
Exxon AK St A1	12997-13182	salt	water		
POINT THOMSON SANDS					
Exxon AK St C1	13424-13560	3400	874	3890	37
Exxon AK St F1	13794-13884	4235	284	14912	35
Ex. Pt.Thom.U1	12834-12874	3860	170	22705	45
	12963-13050	13307	2283	5826	18
Ex. Pt.Thom.U3	13872-13885	6348	476	13336	38
FLAXMAN SANDS					
Exxon AK St A1	12565-12635	2200	2500	864	23
Exxon AK St C1	11476-11600		56	and gas cut mud	
Exxon AK St F1	12008-12080	116	137	1040	22
	12890-12908	64			
Ex. Pt.Thom.U1	11392-11421	2250	132	17045	44
	12048-12282	105 feet sand with good oil shows			
Ex. Pt.Thom.U2	11580-11678	124	248	500	21
Mobil W.Staines	11650-11175	flowed gas and 7 bbl oil			

Unit VI

Unit VI is another shale unit, 13,252 to 12,093. Cuttings are predominantly soft, gray to brown and rarely tan siltstone with minor amounts of tuff and some carbonaceous laminations. Sandstones are very fine-grained, quartzose to cherty with salt and pepper appearance and poorly to well sorted. The logs show sands are very thin and more common at the base of the section. The shale is dark gray to gray, mostly silty and slightly fissile. A trace of dead oil was reported at 12,200.

The gamma-ray and resistivity logs indicate a mostly uniform shale section with minor deflections at the contacts, as if the section contained slightly less clay than the juxtaposed units. The gamma log is 50 ±5 API units and the resistivity log indicates a tight, uniform lithology. DT is 80 ±5 µsec/ft and DTs is 150 ± 10 µsec/ft *(Plate 1)*, with kicks at 12,400, and 12,093. The drilling rate reached, 14 ft/hr at 12,250 but averaged 6 ft/hr. The dipmeter shows minor transport direction towards N and NNW. Mud weight was 13 lbs/gal *(Plate 2)*.

Like the previous section, unit VI has approximately 1 percent TOC. Kerogens are 90 percent amorphous. Thermal maturity indicators are within the catagenetic zone. Despite this, almost no hydrocarbons are produced from cuttings samples during pyrolysis. The indigenous organic matter has low Hydrogen and Oxygen Indexes which are similar to those in overmature sediments. Gas wetness reached almost 80 percent *(Plate 3 and Figure 4)*. This demonstrates that these sediments have low potential to generate hydrocarbons.

Unit VII

Unit VII consists of more thin and interbedded sandstones or siltstones and shale from 12,093 to 11,295. Overall it fines upwards. In the lower part of the unit the beds are thin, but some are distinct on the logs. This characteristic separates it from the underlying unit VI. The sands are light gray with salt-and-pepper appearance to clear or white, very fine grained to fine grained, mostly friable, and well sorted. They commonly have abundant carbonaceous to partially coalified material along bedding planes. The siltstones are soft, light gray to brown with both sandy and carbonaceous laminations . Shales are minor constituents and are gray to dark gray, mostly blocky and have carbonaceous laminations.

The basal contact is fairly distinct on the logs. Both gamma and resistivity suggest a distinct decrease in the amount of clays. Gamma runs 45-50 API units at the base and increases upsection. The resistivity shows the thin distinct beds at the base which becomes mostly shale towards the top. DT runs 75 ± 10 µsec/ft throughout the section with a spike at the top. DTs is 140 ± 20 µsec/ft throughout the sandy parts and 145±5 µsec/ft through the shaley parts. The dipmeter log shows transport directions that are minor and directed NNW-N with a dramatic change at the top of the unit. Drilling rates vary between 4-10 ft/hr and mudweight ran 12.6 lbs/gal (*plates 1* and *2)*. No shows were reported through this interval.

Geochemistry shows less than 1 percent TOC (*Plate 3*). Kerogens are 35 percent to 90 percent amorphous with up to 15 percent Vitrinite. These samples are borderline into the catagenetic phase, but yielded negligible hydrocarbons upon pyrolysis, indicating minimal source rock potential.

Unit VIII

Unit VIII, 11,295 to 10,490, is another subtly defined unit of thin and indistinct interbedded siltstone, sandstone and shale. Contacts are very subdued, and the picks are based largely on the changes in the dipmeter log. The sandstones are too thin to be resolved on any of the geophysical logs. On the mudlog description, they are mostly friable, very fine grained to fine-grained, quartzose to salt and pepper appearance with angular to subangular chert fragments. Siltstones are gray to brown, and commonly have carbonaceous laminations. The shales are gray with silty and carbonaceous laminations.

The gamma log is lower by 5 to 10 API units than units VII and IX. Resistivities are similar. The DT has a basal spike and shows more variation, 80 ± 20 µsec/ft than juxtaposed units. The DTs runs 160 ± 30 µsec/ft. The most distinct change is on the dipmeter log which shows sediment transport direction as NW to undirected. The magnitude or azimuth frequency of transport is not great and is much less than the overlying unit. Drilling rates were 4 to 7 ft/hr. Mudweight was 11.8 to 12.4 lbs/gal. The mudlog reports a thin sand at about 10,750 had a gas show.

TOC's run .5 to 1 percent, from kerogens that are mostly amorphous with 5-10 percent Vitrinite, and 20-30 percent Inertinite. Maturity levels are borderline, but hydrocarbon production indicators are very low and lean. This is similar to the more mature units downsection. Gas Wetness is between 40 and 60 percent. Again, these rocks are lean in TOC and there is little hydrocarbon source potential demonstrated from the organic materials from these rocks.

Unit IX

Unit IX, 10,490 to 9,518, is another subtly defined unit based largely on the characteristic dipmeter log and change in the geochemistry. This unit is comprised of loose, unconsolidated sands, silts and shale with minor amounts of volcanic ash, tuff and black, hard coal. The shale is gray or brown, silty to very silty, hard, and fissile to blocky. The sands are mostly fine- to medium-grained, white, or salt and pepper. Beds are very thin, usually less than a few inches thick. Siltstones are gray, thin bedded to laminated with minor amounts of shale or sandstone, and the bedding is often distorted.

Carbonaceous material and coal are not uncommon along the siltstone laminations. Core #1 recovered 37.5 ft from the 9,674 to 9,634 interval. This lithology is mostly sandstone and siltstone. Both sand and silt are thin-bedded. The sandstones are white to light gray, very fine to fine grained, have salt-and-pepper appearance and are very thin bedded, rarely exceeding inches in thickness. Siltstones are gray to dark gray or black and blocky. What appears to be flaser bedding is common. In addition, there are distorted laminations, perhaps due to syndepositional events.

Through Unit IX, the logs are of a mostly monotonous section. Gamma runs about 55 API units top to bottom which is 10 API units greater than the juxtaposed units. Resistivity is uniform, showing neither distinct contacts nor beds. DT runs 80 to 90 µsec/ft. DTs has a basal spike and runs 170 ± 15 µsec/ft at the base to 190 ± 10 µsec/ft at the top. The dipmeter log shows minor to moderate preference to NW-NNW sediment transport, except at the top of the section where readings are scattered and incoherent. This may be related to the proximity of the change of logging runs, but it also coincides with the major changes in the geochemistry.

If a significant sedimentological change is coincident (i.e. the changes which represent unit IX may be only minor differences in logs' response or background variations), the base of the unit is at 10,940 as transport directions there change noticeably but are of the same size as the underlying section. At the top of this unit the transport directions do not change, but there is a substanstial change to azimuth frequency as it becomes more unimodal and larger than through unit IX.

The top of the unit at 9,518 correlates to some major geochemical changes. TOC's are approximately 1 percent and identical to the rest of the Tertiary section. The pyrolysis data is also similar. However, there is a major change in the thermal regime. Unit IX sediments are mostly mature. They lie beneath a section of sediments that are thermally immature. Gas wetness also increases significantly at the top of Unit IX. There is also a major change in the slope of the %Ro vs. depth line. This change of slope suggests a different thermal regime during burial. In addition, extrapolation of the offset from the 12,600-to-9,518 section, to the surface- to 9,518 section suggests that some 3,000 ft of section has been eroded (Dow, 1974). However, the logs do not show substantial changes to suggest any unconformity, depositional hiatus or change of sedimentation. Thus the changes are mostly geochemical maturation indices rather than coincident to depositional changes.

Unit X

Unit X, 9,518 to 5,985, is a comparitively well defined and coarsening-upwards unit. The section from 9,518 to 7,200 is mostly shale/claystone with very thin and indistinct sands, silts and minor amounts of tuff. From 7,200 to 5,985, the shale is interbedded with sands and silts that are thick enough to show on the logs, but only marginally so. The shale is soft and very silty, brown or gray, and decreases in abundance upsection, giving way to claystone. The clay is soft to gummy, silty, dark gray to brown and it has some carbonaceous laminations. The silts are gray or brown, sandy and are usually laminated.

The base of the section is a subtle difference on gamma and DT logs, but is pronounced on the dipmeter. To approximately 7,200 the section appears as a monotonous shale with hot kicks on the gamma log at 9,050 and lesser ones at 8,782, 8,755, 8,638 and at 8,620. DT has a minor change from 85 to 80 µsec/ft at 8,950. DTs was sporadic. The dipmeter log shows very pronounced NNW transport direction; much greater and more uniform than any other unit. Drilling rates varied between 4 to 30 ft/hr and mudweight varied from 9.8 to 13.4 lbs/gal, with the higher values between 7,250 and 6,950 coincident with a minor gas show (*plates 1 and 2*).

TOC's are a uniform 1 percent, irrespective of the lithological changes in silt, shale or clay content. Kerogens are >80 percent amorphous with only 5-15 percent Vitrinite and up to 5 percent Alginite near about 8000. Thermal maturities are markedly immature, but hydrocarbons are not generated during pyrolysis and thus, there is little source rock potential *(Plate 3 and Figure 4)*.

Unit XI

Unit XI comprises the interval 5,985 to 4,678, which is lithologically identical to the previous unit. The interval is mostly shale at the base and coarsens upwards with a few distinct sandstone or siltstone stringers that are discerneable on the logs. Below 5,405 the unit is mostly soft and silty, gray and gummy claystone with traces of fine-grained, friable sandstone. Up section the claystone becomes siltier with some thin but distinct siltstone units. The siltstones are gray to brown and usually have carbonaceous or woody laminations. There are also traces of fine-grained sandstone. Between 4,650 and 5,050 there are traces of oil in the cuttings .

The base of this unit is picked at the top of the sand/siltstone of the underlying unit picked from the gamma and resistivity logs and a DT kick (110-130 µsec/ft). The basal 600 ft is predominantly shale/claystone. Distinct beds above 5405 are less than 5 ft thick and the agglomerated sands/silts above 4,840 are both very fine-grained or appear to be clay rich on the gamma logs. From 4,678 - 4,890 the logs appear to be mostly thin siltstones. The dipmeter shows predominant, well-developed NNW-NW transport direction, except around 5,500 and the upper contact where it is multidirectional NW, NE, and SE. Drilling rates were as slow as 20 ft/hr in the siltier parts of the section and exceeded 100 ft/hr through the clay rich basal portion. Mudweight was 9.5 lbs/gal. Background gas increased between 4,750 and 5,050, accompanying the traces of oil (*plates 1* and *2*).

TOC's are approximately 1 to 1.5 percent and the indigenous kerogen types are mostly amorphous with 5 to 20 percent Vitrinite and up to 5 percent Exinite *(plate 3)*. These sediments are thermally immature. However, despite the presence of trace amounts of oil in some of the cuttings, few hydrocarbons were liberated during pyrolysis. Except for a minor increase in gas wetness, hydrocarbon indicators show essentially no to low source rock potential for either oil or gas.

Unit XII

Unit XII is claystone from 4,678 to 3,435. The claystone is gray, soft, silty and gummy, with varying amounts of carbonaceous material and floating sand grains. Few sand or silts, even thin, friable stingers occur as distinct units on the logs. The logs show that this is a slightly finer-grained unit overlying Unit XI with few coarse-grained stringers. The top is picked at 3,435 where the gamma and resistivity logs base lines shift to a more clayey, finer-grained lithology. The gamma log runs 60 ± 10 API units, bottom to top and the resistivity suggests a minor coarsening upwards of the unit. DT has a marked basal spike and then runs 110 ± 10 μsec/ft. The dipmeter log shows strongly developed NNW transport direction. Drilling rates decrease steadily down-section from 200 ft/hr to 25 ft/hr. No hydrocarbons were encountered *(plates 1 and 2)*.

TOC's are mostly 1 to 2 percent, making this one of the richest units in the well. Thermal maturities are low and within the diagenetic range. Pyrolysis shows that this is another mostly lean section. However, there are two samples with high(?) Genetic Potential (GP), Production Index (PI) and Hydrogen Index (HI) values suggesting that at least part of this section has hydrocarbon generating capacity, hydrocarbons, or indigenous material with source rock potential. Regardless whether these data represent migrated hydrocarbons, or indigenous material with source rock potential, two samples are volumetrically insignificant and do not appreciably change the overall oil-generating potential of the sediments *(Plate 3 and Figure 4)*.

Unit XIII

Subtle differences in lithology differentiate Unit XIII, 3,435 to 2,385 from the underlying Unit XII. These differences are apparent clay content and the presences of some thin silt or sand stringers. In general the clays are described as soft, silty, gray and gummy with traces of floating, or mostly thin-bedded and unconsolidated sands, silts and some chert pebbles. The siltstones are soft, tan, and as in the core likely to occur in flaser-type bedding with sands and carbonaceous material.

The contacts are relatively (as per the log variations of the Tertiary section) apparent on the logs. Gamma and resistivity show a clay-rich unit. DT increases steadily from 120 at the base to 190 μsec/ft at the top. The DT kick at the top is due to overpressure in the overlying section. It is possibly coincidental with an unconformity. Dipmeter logs show a significant change at 3520 where the well-defined and directed NNW-NW transport direction becomes very small and without predominant preferential direction. But none of the other logs show offsets that correlate to this. Drilling rates averaged 100 ft/hr. DTs varied from 25 to 150 μsec/ft *(plates 1 and 2)*.

TOC's are greater than 1 percent, but decrease downsection to resemble the rest of the well's samples. Kerogens are mostly amorphous with minor amounts of Vitrinite and Exinite. Pyrolysis values are low, and Oxygen Index values increase noticeably upsection *(Plate 3 and Figure 4))*.

Unit XIV

The shallowest logged Unit, XIV, is 2,385 to 930. It consists of more of the same soft, silty and gummy claystone with traces of sandstone. Upsection the mudlog records trace to abundant amounts of wood fragments, peat, and chert pebbles.

addition there are minor amounts of very fine- to coarse-grained sandstone/siltstones.

Overall the gamma and resistivity logs indicate slightly coarser-grained lithologies above 2,385. The most distinct features of unit XIV are the very high resistivity zones,which are unique to this section. Also there is apparent overpressuring as seen on the sonic logs where DT runs 185 ± 5 μsec/ft at the base and 165 μsec/ft at 930. The density log also shows a significant change at 2,385. No dipmeter logs were availavle through this section. Drilling rates ran about 100 ft/hr. The changes to these log characteristics suggest that there is an unconformity at 2,385. However, it is less dramatic than the ones at 17,325 and 15,937.

TOCs from this unit are between 1to 2 percent which is comparatively high for the well. In addition, pyrolysis shows that the hydrocarbons generated from samples through this unit have the highest hydrogen and oxygen index values of almost any samples from the well. These samples plot distinctly as having immature, gas prone kerogens (Banet, in progress) unlike most of the previously described units. This also supports the interpretation that this section above 2,385 is part of a different depositional episode than the rest of the Tertiary rocks.

4. Summary

The Aurora well penetrated 18,325 feet of siliciclastic sediments offshore of the ANWR 1002 area. It is the deepest offshore exploration well in the U.S. Beaufort Sea. There were only minor shows of oil and gas. However there is a wealth of geologic information that is important to the understanding of this area. The well data reveal that there are both some significant stratigraphic similarities and changes which occur across northeast Alaska where nearest onshore data are available, to the south and west.

The deepest unit encountered is most similar in lithology to the Kingak Formation known onshore. It is truncated at 17,325 by an unconformity which is determined to be the LCU of onshore nomenclature. No other interpretation better fits the lithological data and log characteristics.

By comparison to other North Slope wells, the presence of the Kingak Shale at this location suggests that the entire Ellesmerian sequence, which includes the productive intervals at the Prudhoe Bay field, may be present in the large seismically-mapped prospects within the eastern 1002 area of ANWR. The presence of these potential reservoirs would enhance the area's potential for discovery of economically recoverable oil and gas resources.

The next two overlying units are part of the Breakup sequence and resemble productive lithologies identified at the Kuparuk River oil field. By analogy, Units II and III are determined to be lower to middle Cretaceous age. Unit II consists of thin and interbedded sandstones and siltstones that coarsen and thicken upsection into a massive sandstone unit which is informally named the Tapkaurak sand. This sandstone occupies the same stratigraphic position as the Kemik sand or Kuparuk Formation sands. However, the sandstone lithology is much more coarse- grained than the equivalent onshore lithologies. It has common to abundant clear, quartz grains which are subangular to subrounded, with minor amounts of igneous and volcanic rock fragments unlike the Kemik and Kuparuk sands. In this respect, it is lithogically somewhat similar to the Pt. Thomson sand, which is composed of lithic fragments unique to local basement.

Unit III is a thick and mostly brown and gray to black shale which overlies the Tapkruak sandstone. This shaly unit is also very silty, with some pyrite and carbonaceous laminations. But, it lacks the floating quartz grains and chert pebbles commonly associated with the Pebble Shale. The Aurora logs show that it does not have a distinct, highly-radioactive zone (HRZ) like the Pebble Shale, the HRZ of the Ugnuravik Group at Kuparuk or the (upper Cretaceous) Bentonitic Shales of northeast Alaska and the Yukon. Log and lithological similarities suggest that it is related to Unit II and is thus part of the Breakup sequence. Consequently, it is considered no younger than mid-Cretaceous age.

The Cretaceous rocks are terminated by an unconformity at 15,937. Analogy to the Pt. Thomson-Flaxman subsurface suggests that Paleocene age, middle Brookian sequence rocks overlie the mid-Cretaceous Breakup sequence at a Lower Tertiary Unfconformity (LTU). Erosion at this unconformity or non-deposition deletes the upper Cretaceous Bentonitic shales.

Log analysis shows the Tertiary section consists of 11 units. Several are relatively distinct units and the remaining are mostly subtle, coarsening- or fining-upwards Units. Interbedded gray shale and siltstone are the predominant lithologies throughout the entire section. Thick, distinct, coarse-grained units are rare. Without available paleontological data, inferences from local and regional geology are used to separate the middle Brookian, 15,937 to 2,385, from the upper Brookian, 2,385 to the end of data at 930.

The thickest sandstones are found between 14,828 to 14,685, which also recorded an untested gas show. This is the informally-named Oruktalik sand. It is quartzose, white to milky, fine- to coarse-grained with minor amounts of conglomerate. Its thickness, geometry and stratigraphic position correlate well to the hydrocarbon-bearing Flaxman sands.

The remainder of the Tertiary section is uniform. Sediment transport direction is strongly developed to the NNW. Sandstones, siltstones and shales are typically laminated, or thin bedded. Flaser bedding was noted through the cored interval. Distinct (thick enough to be resolved by the logs), coarse-grained units are uncommon. However there were several minor gas shows, oil stains and tar reported. Overpressure zones occur at both the top of the Tertiary section, and at the base, coincident with the Oruktalik sandstone, 14,828 to 14,685.

Reservoir characteristics of the Tapkaurak and Oruktalik sandstones are minimal at this location because of their burial depth. However, their lithologies and stratigraphic positions suggest that they may have significant potential to be good reserviors where burial effects are less severe.

In addition, most Brookian sediments (upper Cretaceous and younger) are typically modeled as having been deposited across the North Slope in a mostly southwest to northeast progradation. In northeast Alaska, sediments such as the Paleocene age Sabbath Creek conglomerates have a marked disposition for only northward transport. The entire Tertiary section at Aurora shows a predominance for northwest or north transport. Above 9,518 transport direction is practically unimodal and towards the northwest *(plate 2)*. This is likely in response to the unique, local tectonics that created the Bulge in the Cordillera (Banet, 1990) from which these Brookian sediments have been shed. The lithogical differences appear to be minimal between the sediments shed from the Bulge and those shed from the rest of the Brooks range.

Consequently, depositional models for northeast Alaska should now account for these distinct north and northwesterly prograding sands. The areas most affected are likely to be the offshore and the 1002 area, where previous exploration models had only considered distal facies of the northeasterly prograding Brookian sediments as viable targets. In addition, the Breakup sequence sands are also well developed in this area.

The geochemical data indicate that the petroleum generating potential throughout Aurora sediments is poor. Amorphous kerogen, rather than any of the identifiable macerals, is the predominant type from cuttings analyses. However, the geochemical data indicate that this amorphous kerogen appears to be predominantly recycled cellulosic material that has minimal petroleum generating potential rather than structureless, sapropelic material which is typically prone to generate liquid hydrocarbons. In contrast, the anomalous C15 extract data indicates that some hydrocarbons are being generated in the area from as yet unidentified sources and that they are migrating through this sedimentary section.

Overall, the Breakup sequence and basal Brookian sediments had the greatest average TOC. Most of the TOC's through both the Middle and Upper Brookian sections are also low; approximately 1 to 2 percent. With noted exceptions, pyrolysis data, the Hydrogen, Oxygen and Production Indexes, and Genetic Potentials are commensurately low.

There are three zones of thermal maturity. The section below approximately 17,500 is overmature. The catagenetic zone is from about 9,518 to 17,500 and the maturity data suggests a complex thermal history through this section. The diagenetic zone is from the surface to 9,518.

Although the geochemistry is not overly favorable for hydrocarbon generation at this location, analogy to the Pt. Thomson area and onshore stratigraphic relations suggest that more favorable conditions should exist to the south. The stratigraphy interpreted from this well suggests that possible reservoir rocks may be similar to the Prudhoe area.

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